8. The Sun as a Star

1. Inside the Sun
2. Solar Energy
3. Solar Activity
The Sun is not only the largest object in our solar system — it is also the nearest example of a star. It produces energy by converting hydrogen to helium, thereby maintaining a constant internal temperature. Particles emitted by the Sun and detected on Earth confirm the details of this picture.
Radius: 
6.9 \times 10^8 \text{ m} 
(109 \text{ times Earth}) 

Mass: 
2 \times 10^{30} \text{ kg} 
(300,000 \text{ Earths}) 

Luminosity: 
3.8 \times 10^{26} \text{ watts}
## Composition of the Sun

<table>
<thead>
<tr>
<th>Number of Atoms</th>
<th>Chemical Symbol</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>H</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>85,000</td>
<td>He</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>850</td>
<td>O</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>400</td>
<td>C</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>120</td>
<td>Ne</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>100</td>
<td>N</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>47</td>
<td>Fe</td>
<td>26</td>
<td>56</td>
</tr>
</tbody>
</table>
I. INSIDE THE SUN

a. How Does the Sun Stay Hot?

b. Two Kinds of Equilibrium

c. Structure of the Sun
How Does the Sun Stay Hot?

Why does the Sun shine?
Because it is hot!
Is it on FIRE? ... NO!

Chemical Energy Content

\[ \frac{\text{Luminosity}}{\sim 10,000 \text{ years}} \]
Is it CONTRACTING? ... NO!

Gravitational Potential Energy

\[ \frac{\text{Luminosity}}{\sim 25 \text{ million years}} \]
\[ E = mc^2 \]

—Einstein, 1905

It is powered by NUCLEAR ENERGY!

Nuclear Potential Energy (core)  
\[ \text{Luminosity} \quad \sim \quad 10 \text{ billion years} \]
Energy From Matter

Matter is frozen energy, and each can be converted to the other. The “rate of exchange” is

\[ E = mc^2 \]

where \( c = 3 \times 10^5 \) km/s is the speed of light.

This applies to any form of energy release, though the fraction of mass converted may be very different:

<table>
<thead>
<tr>
<th>Form of Energy</th>
<th>Example</th>
<th>Fraction Converted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>( \text{H}_2 + \text{O} \rightarrow \text{H}_2\text{O} )</td>
<td>( \sim 10^{-8} )</td>
</tr>
<tr>
<td>Nuclear</td>
<td>( 4 \ p \rightarrow \text{He}^4 )</td>
<td>0.007</td>
</tr>
<tr>
<td>Gravitational</td>
<td>mass ( \rightarrow ) black hole</td>
<td>( \sqrt{v^2 / c^2} )</td>
</tr>
</tbody>
</table>
Two Kinds of Equilibrium

1. Pressure Balance
   - outward gas pressure equals inward gravity

2. Energy Balance
   - energy is generated as fast as it escapes
Gravitational equilibrium:

Energy provided by fusion maintains the pressure.
Pressure Balance

Weight of upper layers compresses lower layers.
Pressure Balance: outward pressure of gas equals inward force of gravity.
Energy Balance:
energy is released in core at same rate as it flows out through ‘surface’.
Gravitational contraction…

provided energy that heated the core as the Sun was forming.

Contraction stopped when fusion began replacing the energy radiated into space.
Structure of the Sun

visible ‘surface’ of Sun: $T \sim 6000 \text{ K}$

The outer layer of Sun’s atmosphere: $T \sim 10^6 \text{ K}$

Energy transport outward by circulating gas

Energy released by nuclear fusion: $T \sim 1.5 \times 10^7 \text{ K}$

Energy transport outward by photons (light)

Note: all layers (except core) have same composition.

charged particles escaping from Sun’s surface
INSIDE THE SUN: SUMMARY

a. How Does the Sun Stay Hot?
   Nuclear reactions; chemical or gravitational energy are inadequate to maintain luminosity for billions of years.

b. Two Kinds of Equilibrium
   Pressure balance (gas pressure vs gravity) and energy balance (production vs outflow) are both needed.

c. Structure of the Sun
   Visible photosphere overlies three internal regions: (1) convection zone, (2) radiation zone, and (3) core.
2. SOLAR ENERGY

a. The Sun’s Core

b. Energy Transport

c. Testing Solar Models
The Sun’s Core

The enormous weight of matter above compresses the core to a density of

$$\rho \approx 150 \text{ gm/cm}^3.$$  

The temperature is

$$T \approx 1.5 \times 10^7 \text{ K}.$$  

Although denser than any solid, the matter in the Sun’s core behaves like a gas. The temperature is so high that atoms are torn apart, forming a ‘sea’ of electrons and atomic nuclei; in other words, a plasma.
A Pint of the Sun

Descriptions of nuclear ‘burning’ in stars sometimes give the impression that the central furnace of a star is a place of violent activity. In fact, the inside of a star is rather peaceful, and hydrogen burning goes on very slowly.

To appreciate this, imagine we had a magic transporter which could beam one pint of gas from the center of the Sun right into this room. One pint of water weighs one pound, but the center of the Sun has a density about 150 times the density of water, so a pint of sun-stuff weighs almost as much as I do.

Now the first thing that would happen is that this building would vanish in a huge explosion. When it was down there in the center of the Sun, the gas was compressed by the vast weight of all the thick layers of dense material above it, so it was under enormous pressure. When it’s suddenly transported to Earth, the confining pressure is removed, and the gas expands — very rapidly. The explosion would have the force of a small nuclear bomb.

So if we want to get this experiment approved by the University administration, we need to make a container which can hold our pint of sun-stuff under pressure without bursting apart. That’s not easy to do, but we’ve already assumed we have a transporter right out of Star Trek, so a little more magic won’t be noticed. But our troubles are not over, because this gas from the center of the sun is incredibly hot, and the heat would escape in the form of X-rays, cooking everyone in the vicinity.

OK, let’s assume we can make the walls of our container perfectly reflective, so that all the escaping heat energy is reflected right back in. I said we were using magic, didn’t I? So we have a pint of sun-stuff sitting right there in front of us, safe as can be. Now let’s allow a little energy to escape — just exactly the amount of energy being generated by nuclear reactions, so the gas stays at a constant temperature. We can use the escaping energy to run a generator and produce electricity. Thermonuclear power!

But before we call a press conference or make any big deals with HECO, we better figure out how much energy those bottled nuclear reactions are generating. And the answer is...

About a thousand times less energy than I’m giving off by being alive. That’s all! Per unit mass, the Sun produces much less energy than a person. In total, the Sun generates a lot of energy, but only because it’s so massive.

Of course, the Sun produces energy by nuclear reactions, while I produce energy by chemical reactions. That’s why the Sun can go on shining for ten billion years, whereas I get hungry every few hours.

The enormous lifetime of the Sun gives us another perspective on the same basic point, which is that nuclear reactions in stars are, for the most part, very slow and gentle. It takes about ten billion years for all the hydrogen in the center of the Sun to be burned to helium. That means that per year, a hydrogen nucleus has about one chance in ten billion of being involved in a nuclear reaction. The center of the Sun is an incredibly safe place for hydrogen nuclei! A hydrogen nucleus in the Sun runs much less risk of undergoing a nuclear reaction than I do of being hit by lightning.
Why so Hot?

Particles move **fast** at **high** temperatures. For hydrogen nuclei to fuse, the temperature must be $\sim 10^7$ K.
Cast of Characters

The **proton** \((p)\), a heavy, positively charged particle; the nucleus of ordinary hydrogen.

The **neutron** \((n)\), a heavy, uncharged particle; found in the nuclei of all atoms other than ordinary hydrogen.

The **positron** \((e^+)\), a light, positively charged particle; the anti-matter equivalent of the electron \((e^-)\).

The **neutrino** \((\nu)\), a very light, uncharged particle.

Hydrogen \((p)\)  Deuterium \((d)\)  Light Helium \(^3\text{He}\)  Helium \(^4\text{He}\)
Proton-Proton Chain

1. Two $p$ fuse to form a $d$, a $e^+$ and a $\nu$.
   This step is very slow; a $p$ must change into an $n$. The $e^+$ will immediately annihilate an $e^-$. 

2. One $p$ and one $d$ fuse, forming $^3\text{He}$ and a photon. 
   This step produces the most energy, carried by the photon.

3. Two $^3\text{He}$ fuse, yielding a $^4\text{He}$ and two $p$. 
Overall Reaction

$4 \, p \rightarrow ^4\text{He} + 2 \, \gamma + 2 \, \nu + 2 \, e^+$

0.7% of mass $\Rightarrow$ energy
The Solar Thermostat

less fusion $\Rightarrow$ temperature falls
pressure drops $\Rightarrow$ core contracts
contraction $\Rightarrow$ core heats up
core heats up $\Rightarrow$ more fusion

more fusion $\Rightarrow$ temperature climbs
pressure grows $\Rightarrow$ core expands
expansion $\Rightarrow$ core cools down
core cools down $\Rightarrow$ less fusion
Pressure balance and energy balance work together to regulate energy production; the sun is stable.
Energy Transport

How does energy get out of the Sun?
Energy Transport: Radiation Zone

Energy is carried out of the radiation zone by photons, which bounce from place to place and slowly diffuse outward.

Moving in a straight line, light could cover this distance in less than two seconds, but the actual path is so twisted that it takes $\sim 10^5$ yr for a photon to escape!
In the convection zone, energy is transported by convection; hot gas rises, cools off, and sinks back. This creates a ‘cellular’ pattern of bright hot spots on the Sun’s photosphere.
Energy Transport: Convection Zone
Testing Solar Models

Our basic picture of the Sun's interior was developed by applying the laws of pressure and energy balance to a sphere of hydrogen and helium of known size, mass, and energy output.

Two powerful tests are now available:

— Helioseismology uses vibrations on the Sun’s surface to probe its interior.

— Solar neutrino detectors measure the reactions in the Sun’s core directly.
Helioseismology

Sound waves created by turbulence echo through the solar interior and shake the ‘surface’.
Helioseismology: Observations

Tiny variations in line-of-sight velocity are detected using the doppler shift. These create the ‘texture’ in this image of the Sun.
Helioseismology: Results

Measured density and temperature agree with models!
Neutrinos (ν) produced by fusion reactions escape the Sun unimpeded and can be detected on Earth.
Recent measurements of neutrinos from the Sun show that fusion is taking place at the expected rate.
Neutrinos: they are very small
They have no charge; they have no mass;
they do not interact at all.
The Earth is just a silly ball
to them, through which they simply pass
like dustmaids down a drafty hall
or photons through a sheet of glass.
They snub the most exquisite gas,
ignore the most substantial wall,
cold shoulder steel and sounding brass,
insult the stallion in his stall,
and, scorning barriers of class,
infiltrate you and me! Like tall
and painless guillotines they fall
down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
from underneath the bed. You call
it wonderful; I call it crass.

Cosmic Gall
From *Telephone Poles and Other Poems*, by John Updike
SOLAR ENERGY: SUMMARY

a. The Sun’s Core

Generates energy via Proton-Proton chain (\(4p \rightarrow \text{He}\)); actively regulates energy production.

b. Energy Transport

Energy random-walks through radiation zone (\(10^5\) yr); carried to surface by hot gas in convection zone.

c. Testing Solar Models

‘Sunquakes’ probe interior and confirm solar models; neutrinos detected on Earth verify reaction rate.
3. SOLAR ACTIVITY

a. The Magnetic Sun

b. Sunspot Cycles

c. Terrestrial Effects
The Magnetic Sun

The Sun rotates and transports energy by convection. In addition, a plasma is a good conductor of electricity.

The Sun generates a strong magnetic field.
Solar Activity: Role of Magnetic Fields

1. Sunspots
   - fields stop convection $\Rightarrow$ surface becomes cooler

2. Solar prominences
   - field lines above photosphere trap flows of plasma

3. Solar flares
   - tangled field lines ‘snap’ $\Rightarrow$ explosive energy release
Sunspots

- cooler (~4500 K) than surrounding photosphere
- have strong magnetic fields (~1000 × ‘normal’)
The **Zeeman Effect** causes single spectral lines to split into three in a strong magnetic field.
Magnetic Fields and Plasma

Compass needles point along field lines.

Charged particles in plasma spiral around field lines.
Sunspots occur in pairs, with bundles of magnetic field lines connecting them.
Prominences contain relatively cool gas confined by magnetic field lines. Some may persist for months; others break up in hours, ejecting mass into space.
Solar Flares

Flares release energy stored in tangled magnetic fields, heating gas above $10^7$ K and ejecting particles at nearly the speed of light.
Sunspot Cycles

The number of sunspots varies with an 11 yr period. Some cycles are much more intense than others.
Cycles of Solar Activity

The Sun spins slightly faster at the equator than the poles. This may slowly ‘wind up’ the magnetic field, triggering cycles of sunspots.
Later in a cycle, spots appear closer to the equator.
Terrestrial Effects: Flares

Major flares may eject charged particles toward Earth, disrupting critical electronic systems.
Low levels of solar activity *may* be associated with cold periods on Earth.

The warming trend since 1980 is *not* due to the Sun!
What About the Current Cycle?

ISES Solar Cycle Sunspot Number Progression
Observed data through Feb 2010

Updated 2010 Mar 4

NOAA: Solar Cycle Progression
Visible Light is Part of the Electromagnetic Spectrum

**Light as a Wave:**
Wavelength ($\lambda$) and frequency ($\nu$) are *inversely* related:

$$\lambda \nu = c$$

Light’s speed ($c$) and Planck’s constant ($h$) are *always* constant.

**Light as a Particle:**
Frequency ($\nu$) and energy ($E$) are *directly* related:

$$E = h \nu$$